

Submesoscale Flows and Mixing in the Ocean Surface Layer Using the Regional Oceanic Modeling System (ROMS)

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LONG-TERM GOALS

The long-term goals of this project are to further the insight into the dynamics of submesoscale flow in the oceanic surface layer. Using the regional oceanic modeling system (ROMS) we aim to understand the impact of submesoscale processes on the mixing at small scales of tracers and the transfer of energy towards the dissipative scales of non-geostrophic turbulence. An advanced understanding of surface layer processes at these small scales is instrumental in interpreting remote and directly sensed observations that are increasingly capable of observing submesoscale flows. These goals accompany the continuation of the evolution of the Regional Oceanic Modeling System (ROMS) as a multi-scale, multi-process model and utilizing it for studying a variety of oceanic phenomena that span a scale range from turbulence to basin-scale circulation.

OBJECTIVES

- Further development of the non-hydrostatic component of ROMS is required to increase efficiency. The non-hydrostatic ROMS involves the solution of a three dimensional Poisson problem for the non-hydrostatic pressure at each baroclinic time step. The current discrete Poisson matrix is asymmetric and not particularly well conditioned and therefore requires a general and robust method for its solution. For larger grid sizes, solving this Poisson problem represents the majority of the computational cost involved in running ROMS. We are also aiming to improve the numerical properties of the poisson operator with regards to energy conservation and further reduce pressure gradient errors near topographic slopes.
- As the size of the grid scale is further reduced by either larger computational grid of successively nested domains, the need for further investigation of sub-grid scale parameterizations is necessary. The KPP scheme has been extensively used for many oceanic studies and for a wide range of applications. This is appropriate when the scales that are explicitly resolved by the model do not include the dominant mixing processes such as those induced by static instability and wind-driven mixing. For the computational regime where those processes can be partially, but not yet fully resolved, it will require the use of alternative subgrid scale parameterizations.
- We aim to provide appropriate, physically relevant boundary conditions for our finest scale simulations. Our approach to obtain these is to continue the practice of computing eddy

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resolving basin scale solution and subsequently compute nested solutions down to the required scales.

- Our focus is on situations where mesoscale energy transfer exchange with submesoscale unbalanced motions is likely to occur. Our goal is to identify the regimes of submesoscale flows in the ocean surface layer.
- In the context of the ONR DIR program; "Lateral Mixing a Small Scales", we aim to perform targeted simulations of the North Western Atlantic that are in direct support of observations in that area. The solutions will be used to test a variety of sampling strategies by performing virtual experiments using the numerical data. In this way, it is possible to test in advance whether features (such as, for instance, the relative vorticity field at a scale of 1 km) can be determined with a particular choice of observational strategy. Which strategy is preferred will depend on the phenomena studied and its associated spatial and temporal scales of coherency.

APPROACH

Computational simulation of oceanic currents and material distributions is an important and evolving tool in the geosciences. ROMS is a loosely coordinated modeling approach with a substantial international community of scientific developers and users (<http://www.myroms.org/>). ROMS is a generalized terrain-following coordinate, primitive-equation oceanic model that is implemented as a modern, efficient parallel code, and it is accompanied by an infrastructure of pre-, post-processing, and visualization tools. ROMS provides a test-bed for some of the most innovative algorithms and parameterizations, and it probably is now the most widely used model among academic researchers for regional, high-resolution simulations of highly turbulent flows. We, at UCLA, are among the lead architects of ROMS (Shchepetkin and McWilliams, 1998, 2003, 2005, 2008, 2011). Our approach is problem-driven: the algorithmic formulation and code implementation are advanced to meet the requirements for simulating particular processes and phenomena.

As model changes are made through a sequence of problems, the capabilities of ROMS expand to make it a more robust simulation tool, encompassing a wider range of coupling linkages with the circulation physics.

Using our nesting capabilities, we are uniquely qualified to study phenomena that range in scales that are between boundary layer turbulence and mesoscale eddy flows. These type of phenomena are difficult to model because they require very high numerical resolution, but additionally, there is a need for a non-trivial mesoscale flow to provide the lateral tracer gradients and velocity straining fields required to provide a realistic environment in which these ocean phenomena exist. We have fine-tuned a computational approach that relies on multi-leveled nested solutions to arrive at this flow regime, which has been elusive for modelers until now.

WORK COMPLETED

In the past year, we have successfully completed detailed realistic simulations of several local regions in the Atlantic as well as the Pacific Ocean. Using the nested computational approach described above, we have computed high resolution solutions (down to 150 m resolution) in the Brazil current near Rio de Janeiro, the Gulf Stream, both upstream and downstream of the separation point at cape Hatteras, in the Kuroshuo current system near Japan, and the Solomon Sea in the South West Pacific. We have advanced our suite of diagnostic tools, using a Python-Fortran hybrid approach. Energy a

new off-line Lagrangian float tracking tool was implemented that was using extensively to detect mixing events, quantify mixing rates, and using particle tracking, backwards in time, verifying the origin of water masses. We have also made important progress on the study of the role of pressure in the presence of topographic features. From an algorithmic point of view, we are in the late stages of testing and verifying an alternative approach to terrain following numerical models. In a series of simulations of flows past idealized features such as Gaussian Seamounts, we are examining the boundaries of numerical reliability of the standard formulation of ROMS by comparison to alternative approaches such as used by the MITgcm model and a new class of boundary fitted numerical discretizations.

RESULTS

We present a few highlights for this project. The publications list (papers from 2012 up to ones likely to be submitted in 2013) provides a view of the finalized results across all our ONR projects.

The life cycle of cold filaments in the Gulf Stream

Realistic high resolution simulations show that filaments are numerous in nature and dynamically active. The frontogenesis tendencies are strain induced with horizontal advection as the largest contributor. Vertical mixing opposes the frontogenetic effect of advection at the center, but has a positive signal on the exterior sides of the filaments. Vertical straining weakens the fronts everywhere but is significant only at depth. Horizontal diffusion also weakens the front, and is largest at the surface where the velocity shear is also maximum. Filamentogenesis can be understood in terms of a dual frontogenetic process, along the lines described in the results for single fronts of Capet et al. (2008). There is however a stronger asymmetry due to the amplification at the center of the filament. Filaments dynamics is not adequately described by the classical thermal wind balance. The effect of vertical mixing of momentum due to turbulence in the surface layer is of the same order of magnitude as the pressure gradient and vertical shear terms in the upper oceanic layer and contributes equally to a so-called turbulent thermal wind balance. Filamentogenesis is disrupted by vigorous submesoscale instabilities (see Fig. 1). Energy production by the horizontal Reynolds stress is the primary mechanism during the process. The source of the instability is of lateral shear which is different from the frontal cases of Capet et al. (2008) where baroclinic conversion is the driving force of the frontal instabilities. Injection of negative potential vorticity by the wind is visibly present in our simulations but does not appear to be essential to the filament life-cycle described here. Negative PV is a condition for the onset of symmetrical instability, which may not be well resolved even at such resolution ($dx = 150m$). These filaments are lines of strong oceanic surface convergence as illustrated by the release of Lagrangian parcels at the surface of the Gulf Stream. Diabatic mixing is strong as parcels move across the filaments and down-well into the pycnocline.

Shingle Eddies on the shelf break upstream of Cape Hatteras

Frontal eddies propagate along the inshore edge of the Gulf Stream until squeezed by the 163 narrow shelf at Cape Hatteras. The cyclonic circulation in the eddy interacts with the leading wave crest and entrains a warm streamer or filament around the west side of the eddy which results in a contortion of the Gulf Stream thermal front in to a series of "shingles" shapes as first described by Von Arx et al. (1955). A sequence of SST snapshots from a ROMS numerical simulation is plotted in Figure 3, showing the evolution of the frontal eddy, initially at 33N, 77W in subsequent panels with 2.5 day intervals. The frontal eddy cross-shelf and alongshore scales are about 50km and 100km,

respectively, and it propagates downstream at 24 km/day. The offshore side of the frontal eddy follows the 600m isobath. When the eddy converges toward Cape Hatteras, it is squeezed against the shelf and ultimately sheared apart as the slope becomes increasingly steep. Clearly visible is the cold upwelled water in the meander through, and the shallow warm filament ("shingle") detached from the wave crest at the surface along the shoreward side of the cold dome A reason for the weakening of the frontal eddy on its path to Cape Hatteras might be due to the deeper slope which decreases the intensity of the upwelling. Small scale perturbations around the rim of the frontal eddy can be seen in Figure 3(b). The frontal eddy is unstable to smaller scale instabilities around its rim. These modes are mixed layer instabilities that are essentially geostrophic in nature but have a smaller horizontal scale due to the reduced scale of the Rossby deformation radius in the mixed layer. The small scale rim instability is remarkably persistent throughout the life cycle of the frontal eddy.

Comma Instabilities on the North wall of the Gulf Stream

As part of the ONR program on small scale lateral mixing we were fortunate enough to directly collaborate with observational efforts in the winter time North Western Atlantic. One of the results of this cooperation was the successful observation and numerical simulation of a new phenomena on the North Wall of the Gulf Stream (Figure 4). The comma instability can be shown to be driven by the release of potential energy through mixed layer baroclinic instabilities. The instability predominantly occurs on the upstream faces of the Gulf Stream meanders. A process of North Wall frontogenesis and surface convergence functions as a strong stabilizing agent on the downstream sides of the large scale meanders. The comma instabilities interleave water with alternating positive and negative salinity anomalies. Using the approach of tracking Lagrangian particles backwards in time, we can determine the origin of these anomalous water masses that become embedded in the core of the Gulf Stream. Analysis shows that the anomalies are a result of the mixing of relatively fresh surface water from an area north of the Gulf Stream and relatively salty, subsurface water that originates from the Gulf Stream core. Experiments with large numbers of particle releases reveal the existence of events of enhance mixing across the North Wall front, possibly revealing a alternate source of 18 degree mode water.

Statistics of Submesoscale Turbulence

Following a series of tests of observational strategies to observe submesoscale turbulence statistics, a detailed view of upper ocean vorticity, divergence, and strain statistics was obtained by a two-vessel survey in the North Atlantic Mode Water region in the winter of 2012. Synchronous Acoustic Doppler Current Profiler sampling provided the first in situ estimates of the full velocity gradient tensor at $O(1 \text{ km})$ scale without the usual mix of spatial and temporal aliasing. The observed vorticity distribution in the mixed layer was markedly asymmetric (skewness 2.5), with sparse strands of strong cyclonic vorticity embedded in a weak, predominantly anticyclonic background. Skewness of the vorticity distribution decreased linearly with depth, disappearing completely in the pycnocline. Statistics of divergence and strain rate generally followed the normal and chi distributions, respectively. These observations confirm our model prediction for the structure of the active submesoscale turbulence field in this area.

The model predictions matched the mixed layer observations of distributions of vorticity, divergence, and strain rate very well (Figure 5). However, below the mixed layer observed distributions were wider than their model counterparts. The observed gradual decrease of relative vorticity skewness with depth was qualitatively similar to the numerical results, but the change of sign of vorticity

skewness at 250 – 350 m depth predicted was not visibly present in our observations. Discrepancies between the model and observations in the upper pycnocline can be attributed to the underrepresentation of inertia-gravity waves (IGW) by the model and to the reduced signal-to-noise ratio in the deeper ADCP data (see the instrument noise discussion in supporting information). IGW deficit in the model can be illustrated by comparing the observed and model spectra of horizontal velocity and vertical vorticity. In the mixed layer, the model reproduced the observed spectra well, suggesting adequate simulation of submesoscale dynamics and a weak IGW signal. This is consistent with the expected low IGW signal in a deep mixed layer (see supporting information). In the upper pycnocline, the observed spectra were close to those predicted by Garrett and Munk with buoyancy frequency $N = 4 \times 10 s^{-1}$, while the model spectra were 510 times lower at scales 20 km, indicating a deficiency of short IGW. Since the model forcing does not include high-frequency wind stress variations or tides, the two major sources of internal wave energy, and has a relatively coarse grid resolution (with respect to the GM spectrum), model underrepresentation of IGW is not surprising. The observed near-surface vorticity distribution in the NAMW region in winter was substantially more asymmetric than that found in previous submesoscale observations. LatMix observations were in excellent agreement with numerical model predictions for active submesoscale turbulence in this region.

IMPACT/APPLICATIONS

Geochemistry and Ecosystems: An important community use for ROMS is biogeochemistry: chemical cycles, water quality, blooms, micro-nutrients, larval dispersal, biome transitions, and coupling to higher tropic levels. We collaborate with Profs. Keith Stolzenbach (UCLA), Niki Gruber (ETH), Curtis Deutsch (UCLA), David Siegel (UCSB), and Yusuke Uchiyama (Kobe).

Data Assimilation: We collaborate with Drs. Zhinjin Li (JPL), Yi Chao (Remote Sensing Solutions), and Kayo Ide (U. Maryland) by developing model configurations for targeted regions and by consulting on the data-assimilation system design and performance. Current quasi-operational, 3DVar applications are in California (SCCOOS and CenCOOS) and in Alaska (Prince William Sound).

TRANSITIONS

ROMS is a community code with widespread applications (<http://www.myroms.org>).

RELATED PROJECTS

Three Integrated Ocean Observing System (IOOS) regional projects for California and Alaska (SCCOOS, CenCOOS, and AOOS) are utilizing ROMS for data assimilation analyses and forecasts.

PUBLICATIONS

Bracco, A., J. D Neelin, H. Luo, J. C. McWilliams, and J. E. Meyerson, 2013: High dimensional decision dilemmas in climate models. *Geosci. Model Dev.*, **6**, 2731-2767, doi:10.5194/gmdd-6-2731-2013.

Buijsman, M.C., Y. Uchiyama, J. C. McWilliams, and C. R. Hill-Lindsay, 2012: Modeling semidiurnal internal tide variability in the Southern California Bight. *J. Phys. Oceanogr.* **42**, 62-77, doi:10.1175/2011JPO4597.1

Chekroun, M. D., J. D. Neelin, D. Kondrashov, J. C. McWilliams, and M. Ghil, 2013: Rough parameter dependence in climate models: The role of Ruelle-Pollicott resonances. *Proc. Nat. Acad. Sci.*, submitted.

Colas, F., J.C. McWilliams, X. Capet, and J. Kurian, 2012: Heat balance and eddies in the Peru-Chile Current System. *Climate Dynamics* **39**, 509-529, doi:10.1007/s00382-011-1170-6.

Colas, F., X. Capet, J.C. McWilliams, and Z. Li, 2013a: Mesoscale eddy buoyancy flux and eddy-induced circulation in eastern boundary currents. *J. Phys. Oceanogr.* **43**, 1073-1095, doi:10.1175/JPO-D-11-0241.1.

Colas, F., X. Wang, X. Capet, Y. Chao, and J.C. McWilliams, 2013b: Untangling the roles of wind, run-off and tides in Prince William Sound. *Continen. Shelf Res.*, **63**, S79-S89, doi:10.1016/j.csr.2012.05.002.

Dong, C., X. Lin, Y. Liu, F. Nencioli, Y. Chao, Y. Guan, T. Dickey, and J. C. McWilliams, 2012: Three-dimensional oceanic eddy analysis in the Southern California Bight from a numerical product. *J. Geophys. Res.*, **117**, C00H14, doi:10.1029/2011JC007354.

Farrara, J., Y. Chao, Z. Li, X. Wang, X. Jin, H. Zhang, P. Li, Q. Vu, P. Olsson, C. Schoch, M. Halverson, M. Moline, C. Ohlmann, M. Johnson, J. C. McWilliams, and F. Colas, 2013: A data-assimilative ocean forecasting system for the Prince William Sound and an evaluation of its performance during Sound Predictions 2009. *Continental Shelf Research*, **63**, S193-S208, doi:10.1016/j.csr.2012.11.008.

Gula. J., M. J. Molemaker, and J. C. McWilliams, 2013a: Mean dynamic balances in the Gulf Stream in high-resolution numerical simulations, *in preparation*.

Gula. J., M. J. Molemaker, and J. C. McWilliams, 2013b: Gulf Stream dynamics and frontal eddies along the Southeast U.S. continental shelf, *in preparation*.

Gula. J., M. J. Molemaker, and J. C. McWilliams, 2013c: Submesoscale cold filaments in the Gulf Stream, *in preparation*.

Gula. J., M. J. Molemaker, and J. C. McWilliams, 2013d: Submesoscale instabilities on the Gulf Stream north wall. *in preparation*.

Lemarié, F., J. Kurian, A.F. Shchepetkin, M.J. Molemaker, F. Colas, and J. C. McWilliams, 2012a: Are there inescapable issues prohibiting the use of terrain-following coordinates in climate models? *Ocean Modelling* **42**, 57-79, doi:10.1016/j.ocemod.2011.11.007.

Lemarié, F., L. Debreu, L., A.F. Shchepetkin, and J.C. McWilliams, 2012b: On the stability and accuracy of the harmonic and biharmonic adiabatic mixing operators in ocean models. *Ocean Modelling* **52-53**, 9-35, doi:10.1016/j.ocemod.2012.04.007.

Li, Z., Y. Chao, J. Farrara, and J. C. McWilliams, 2013: Impacts of distinct observations during the

2009 Prince William Sound field experiment: A data assimilation study. *Continental Shelf Research*, **63**, S209-S222, doi:10.1016/j.csr.2012.06.018

Li, Z., Y. Chao, J. McWilliams, K. Ide, and J. D. Farrara, 2012: A multi-scale three-dimensional variational data assimilation and its application to coastal oceans. *Q. J. Roy. Met. Soc.*, submitted.

Li, Z., Y. Chao, J.C. McWilliams, K. Ide, and J. Farrara, 2012: Experiments with a multi-scale data assimilation scheme. *Tellus Series A: Dynamic Meteorology and Oceanography*, submitted.

Liang, J.-H., J. C. McWilliams, P. P. Sullivan, and B. Baschek, 2012: Large Eddy Simulation of the bubbly ocean: Impacts of wave forcing and bubble buoyancy. *J. Geophys. Res.* **117**, C04002, doi:10.1029/2011JC007766.

Liang J.-H., J. C. McWilliams, J. Kurian, P. Wang, and F. Colas, 2012: Mesoscale variability in the Northeastern Tropical Pacific: Forcing mechanisms and eddy properties. *J. Geophys. Res.* **117**, C07003, doi:10.1029/2012JC008008.

Liang, J.-H., C. Deutsch, J. C. McWilliams, B. Baschek, P. P. Sullivan, and D. Chiba, 2013: Parameterizing bubble-mediated air-sea gas exchange and its effect on ocean ventilation. *Glob. Biogeo. Cycles*, **27**, doi:10.1002/gbc.20080.

McWilliams, J. C., E. Huckle, J. Liang, and P. P. Sullivan, 2012: The wavy Ekman layer: Langmuir circulations, breakers, and Reynolds stress. *J. Phys. Oceanogr.* **42**, 1793-1816, doi:10.1175/JPO-D-12-07.1.

McWilliams, J. C., and B. Fox-Kemper, 2013: Oceanic Wave-balanced surface fronts and filaments. *J. Fluid Mech.*, **730**, 464-490, doi:10.1017/jfm.2013.348.

McWilliams, J. C., E. Huckle, J. Liang, and P. P. Sullivan, 2013: Langmuir Turbulence in swell. *J. Phys. Oceanogr.*, submitted.

Mechoso, C. R., R. Wood, R. Weller, C. S. Bretherton, A. D. Clarke, H. Coe, C. Fairall, J. T. Farrar, G. Feingold, R. Garreaud, C. Grados, J. McWilliams, S. P. de Szoeke, S. E. Yuter, and P. Zuidema, 2013: Ocean-Cloud-Atmosphere-Land Interactions in the Southeastern Pacific: The VOCALS Program. *Bull. Amer. Met. Soc.*, doi:10.1175/BAMS-D-11-00246.1.

Menesguen, C., J. C. McWilliams, and M. J. Molemaker, 2012: An example of ageostrophic instability in a rotating stratified flow. *J. Fluid Mech.*, **711**, 599-619, doi:10.1017/jfm.2012.412.

Molemaker, M. J., J. C. McWilliams, and W. K. Dewar, 2013: Submesoscale instability and generation of mesoscale anticyclones near a separation of the California Undercurrent. *J. Phys. Oceanogr.*, submitted.

Molemaker, M. J., J. C. McWilliams, and W. K. Dewar, 2013: Centrifugal instability and mixing in the California Undercurrent. *J. Phys. Oceanogr.*, submitted.

Romero, L., Y. Uchiyama, J. C. Ohlmann, J. C. McWilliams, and D. A. Siegel, 2013: Simulations of nearshore particle-pair dispersion in Southern California. *J. Phys. Oceanogr.* **43**, 1862-1879, doi:10.1175/JPO-D-13-011.1.

Roulet, G., J. C. McWilliams, X. Capet, and M. J. Molemaker, 2012: Properties of equilibrium geostrophic turbulence with isopycnal outcropping. *J. Phys. Oceanogr.* **42**, 18-38, doi:10.1175/JPO-D-11-09.1.

Shcherbina, A. Y., E. A. D'Asaro, C. M. Lee, J. M. Klymak, M. J. Molemaker, and J. C. McWilliams, 2013: Statistics of vertical vorticity, divergence, and strain in a developed submesoscale turbulence field. *Geophys. Res. Lett.*, **40**, doi:10.1002/grl.50919.

Sullivan, P. P., L. Romero, J. C. McWilliams, and W. K. Melville, 2012: Transient evolution of Langmuir Turbulence in ocean boundary layers driven by hurricane winds and waves. *J. Phys. Oceanogr.* **42**, 1959-1980, doi:10.1175/JPO-D-12-025.1.

Sullivan, P. P., J. C. McWilliams, and E. G. Patton, 2013: A high-Reynolds number Large Eddy Simulation model of the marine atmospheric boundary layer above a spectrum of moving waves, in preparation.

Uchiyama, Y., E. Idica, J. C. McWilliams, and K. Stolzenbach, 2013: Wastewater effluent dispersal in two Southern California Bays. *Cont. Shelf Res.*, submitted.

Wang, P., J. C. McWilliams, and Z. Kizner, 2012: Ageostrophic instability in rotating shallow water. *J. Fluid Mech.*, **712**, 327-353, doi:10.1017/jfm.2012.422.

Wang, P., J. C. McWilliams, and C. Ménesguen, 2013: Ageostrophic instability in rotating, stratified interior vertical shear flows. *J. Fluid Mech.*, submitted.

Wang, X., Y. Chao, H. Zhang, J. Farrara, Z. Li, X. Jin, K. Park, F. Colas, J. C. McWilliams, C. Paternostro, C.K. Shum, Y. Yi, C. Schoch, and P. Olsson, 2013: Modeling tides and their influence on the circulation in Prince William Sound, Alaska. *Continental Shelf Research*, **63**, S126-S137, doi:10.1016/j.csr.2012.08.016.

FIGURES

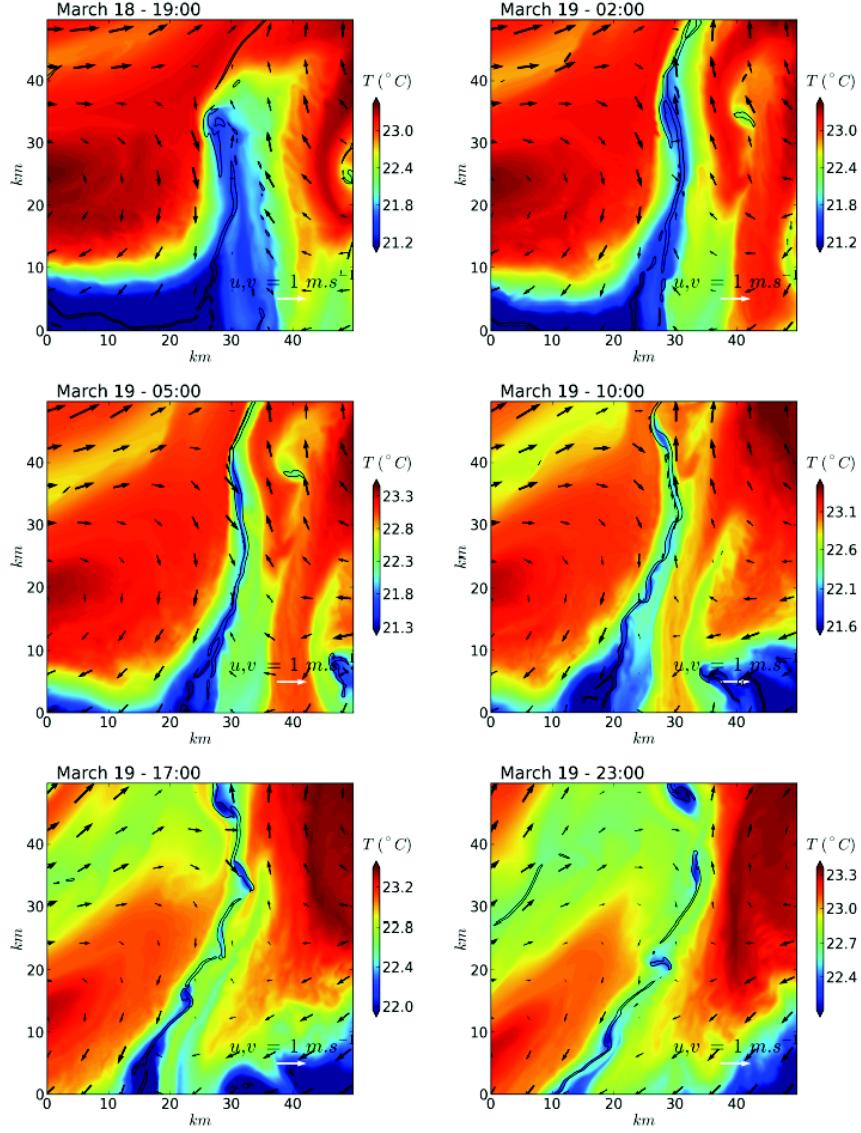


Figure 1: *SST (in colors), surface relative vorticity (black contours) and surface velocity (vectors) for the evolution of a cold filament in the winter time Gulf Stream, upstream of Cape Hatteras. The vectors show the horizontal velocity anomalies for the domain shown. Note the initial sharpening of the cold filament after which the onset of a shear driven instability limits the filamentogenetic process. The total life cycle of sharpening, instability and breakdown takes place in about 24 hours.*

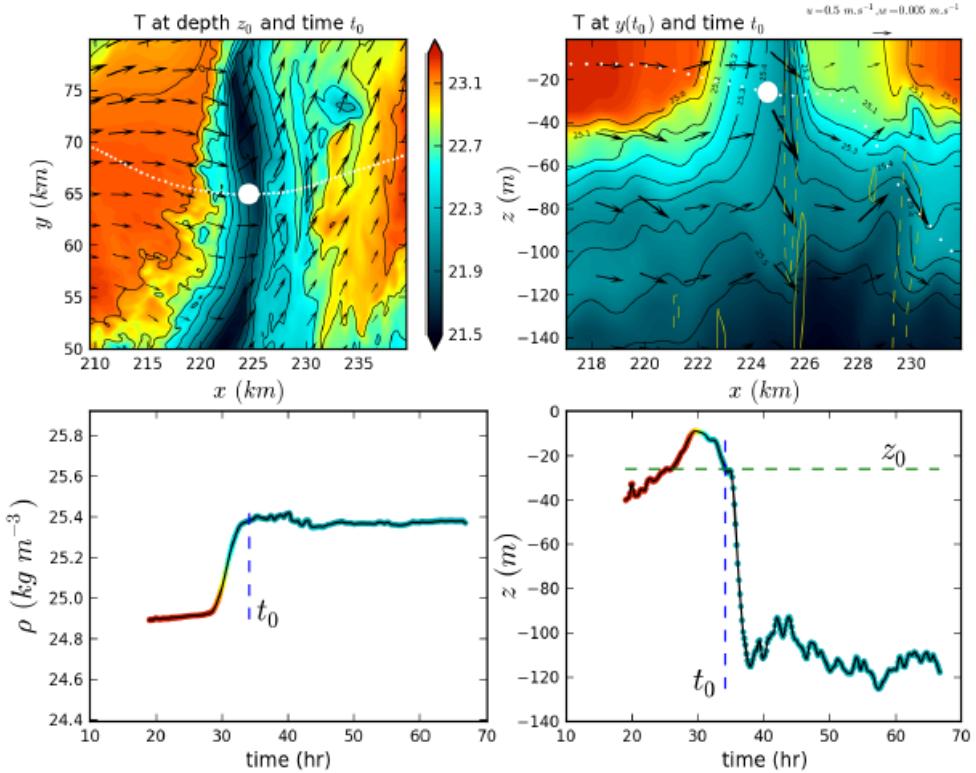


Figure 2: *Upper panels: Temperature (K, colors), density anomaly (black contours) and velocity (vectors) in the horizontal (left) and vertical (right) planes centered on the position of one Lagrangian particle (marked as a yellow dot) at time $t = t_0$. Smaller black dots show the past and future position of the particle. Yellow contours on the upper right panel show the vertical velocity. Lower panels: Density (left) and depth (right) evolution of the particle with time. Colored dots show the temperature of the particle at the corresponding position using the same color scale as in the upper panels.*

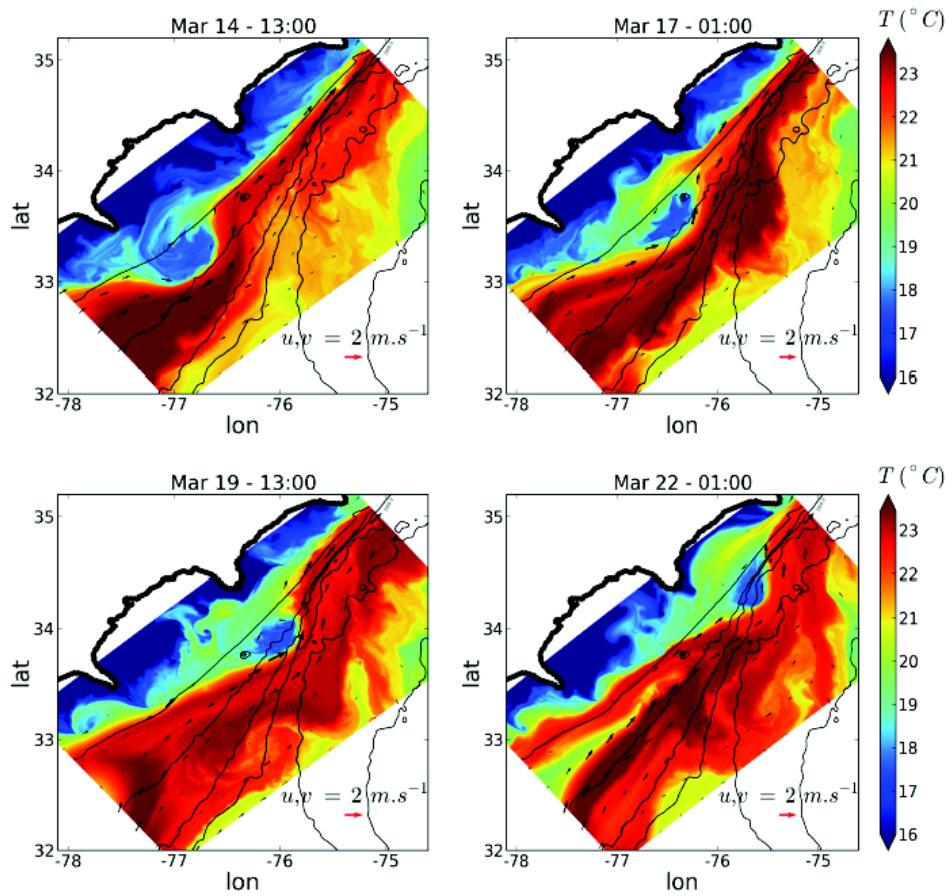


Figure 3: *Simulated Sea Surface Temperature (SST) for the region south of the Gulf Stream separation point at Cape Hatteras at four different times every 2.5 days. Surface velocities are the black vectors. Topography is shown in black contours for levels 10m, 200m, 600m, 1000m, 2000m, 3000m, 4000m*

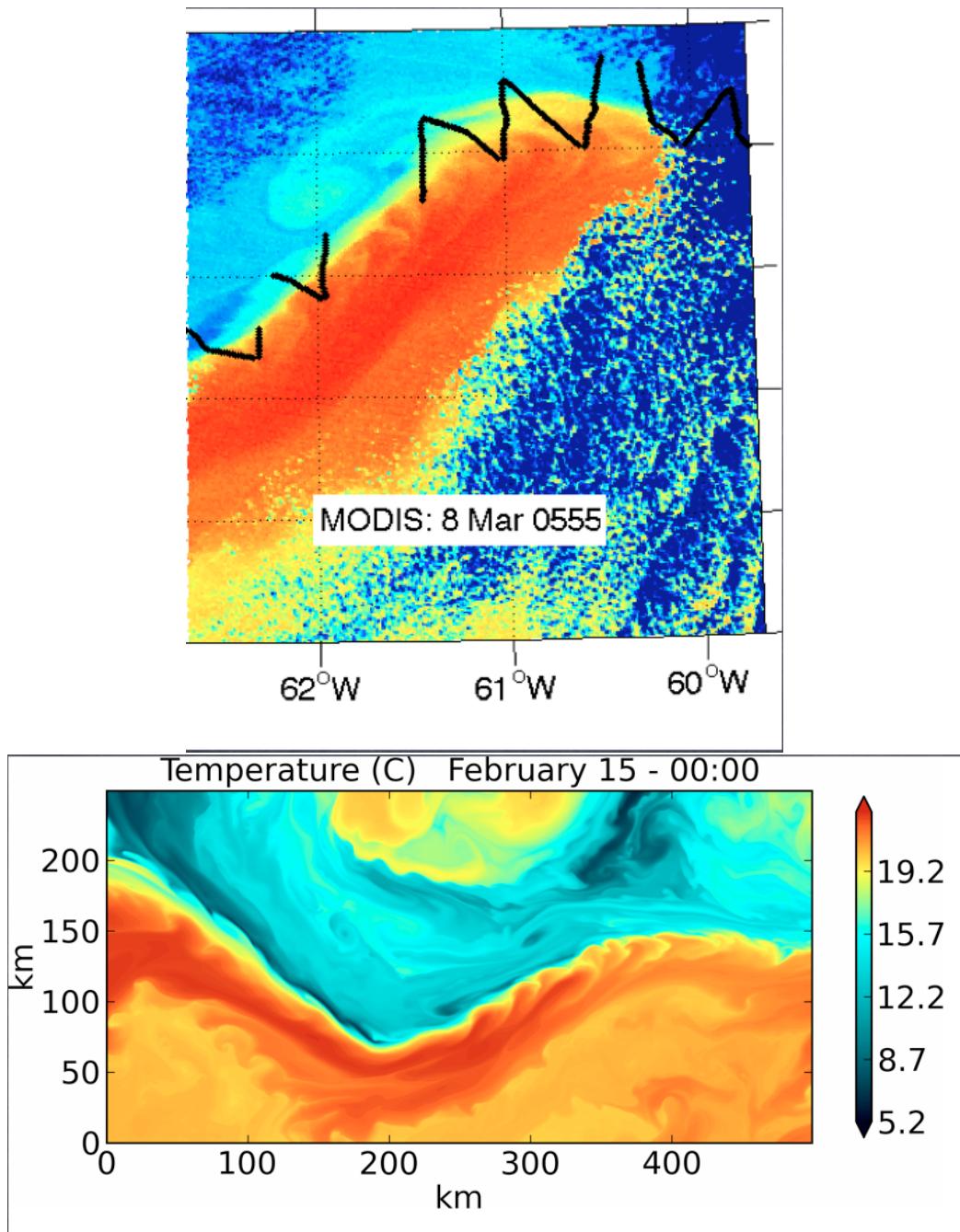


Figure 4: *Upper panel: SST as observed by the modis satellite on March 8, 2012. Partial ship tracks of LatMix observations are shown as solid black lines. Visible in the image are the comma like cold surface intrusions. Lower panel: Numerical simulation of a winter time Gulf Stream. SST shows the emergence of comma instabilities on the north wall. Analysis shows these instabilities to be driven by surface mixed layer baroclinic instabilities. Lagrangian particle releases reveal that these instabilities may be a significant source of cross North Wall mixing and a potential alternate source of 18 degree mode water.*

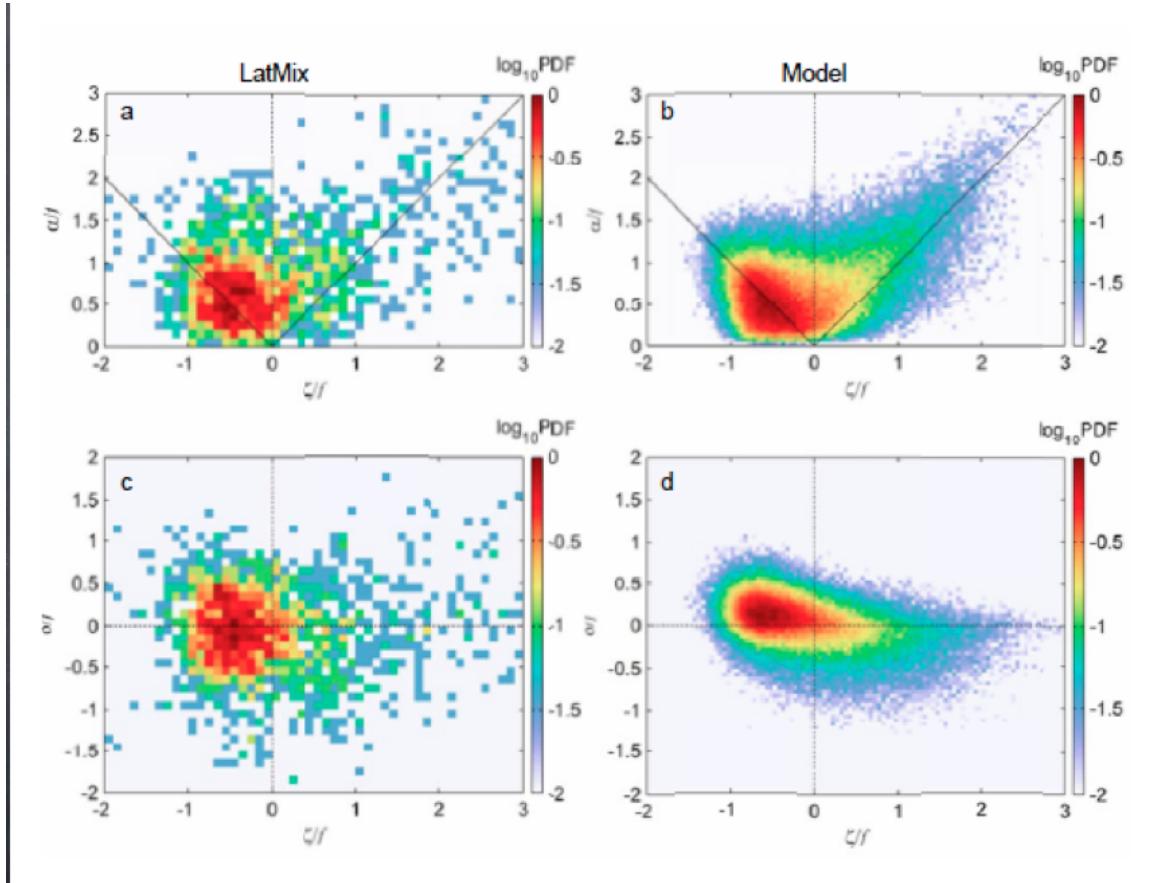


Figure 5: *Joint probability distribution functions (JPDFs) of (a, b) vorticity and strain rate and (c, d) vorticity and divergence in the mixed layer (050 m) based on LatMix 300 kHz ADCP observations (Figures 5a and 5c) and the numerical model (Figures 5b and 5d). Black dotted lines in Figures 5a and 5b correspond to one-dimensional shear flow; horizontal axes correspond to solid body rotation. All JPDFs are normalized by their maximum values.*